



Simulation of Flywheel Energy Storage System Controls

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This report is a formal draft or working paper, intended to solicit comments and ideas from a technical peer group.

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ABSTRACT

This paper presents the progress made in the controller design and operation of a flywheel energy storage system [1]. The switching logic for the converter bridge circuit has been redefined to reduce line current harmonics, even at the highest operating speed of the permanent magnet motor-generator. An electromechanical machine model is utilized to simulate charge and discharge operation of the inertial energy in the flywheel. Controlling the magnitude of phase currents regulates the rate of charge and discharge. The resulting improvements are demonstrated by simulation.

INTRODUCTION

A flywheel energy storage system is being considered as a replacement for the traditional electrochemical battery system in spacecraft electrical power systems. The flywheel system is expected to improve both the depth of discharge and working life by a factor of 3 compared with its battery counterpart [2]. Although flywheels have always been used in spacecraft navigation and guidance systems, their use for energy storage is new. However, the two functions can easily be combined into a single system. The NASA Glenn Research Center [3], in a cooperative activity with industry and academia, has spearheaded a developmental effort that will culminate in an experiment to replace one battery pack on the International Space Station (ISS) with a flywheel unit. Simulation of the flywheel system operation in support of this effort continues.

In previously reported work [4], the charging and discharging process between the electrical machine and the dc bus, via the converter, was simulated to show the power transfer that takes place in the respective modes. However, the electrical machine was a circuit element and not an electromechanical device. Thus, inertial energy transfer could not be simulated as a continuous function of machine speed. Also, the harmonic content of the motor phase currents was much too high to be easily corrected by filters alone.

This paper addresses both of the above problems. Using an electromechanical machine model, inertial energy storage and transfer is simulated as a function of rotational speed. Similarly,

the converter switching logic has been redefined to substantially reduce phase current harmonic content to a manageable level.

SYSTEM DESCRIPTION

The simulated flywheel energy storage system (Fig. 1) consists of a flywheel that is shaft-coupled to a permanent magnet, three-phase, synchronous motor-generator unit. The motor-generator unit is powered by a dc source through a three-phase, bidirectional, half-bridge converter. In the charge mode, energy is transferred from the dc source to the flywheel by increasing the flywheel rotational speed. The reverse operation takes place during the discharge mode. Under the current design, the flywheel operating speed will be between 20 000 (min.) and 60 000 (max.) rpm. Since the inertial energy stored in a flywheel varies as the square of its rpm, it can discharge 90 percent of its maximum stored energy from maximum to minimum speed limits. The flywheel rotational inertia constant selection is based on energy storage requirements. Reliability and safety considerations govern the maximum speed limit; further lowering of the minimum limit does not yield much additional depth of discharge. Friction and winding losses are assumed to be insignificant.

The voltage magnitude and frequency at the machine terminals are directly proportional to the speed of rotation. Therefore, control of the converter operation determines the motoring (charge) or generating (discharge) action as desired. The phase current magnitude and phase angle determine the amount and the direction of power, respectively. This is achieved by pulse width-modulated (PWM) switching of the converter switches. The switching action is also affected by the rotor position (actually, by the position of the magnet pole axis with respect to the phase A winding axis). Such control is known as "closed-loop control." A detailed explanation of the controller will be given in the following section.

Nominal filter circuits are connected on the dc side of the converter. These have not yet been tuned to further reduce harmonic contents of the dc bus voltage or current. A series-connected inductive filter is utilized to reduce the harmonic content of the phase windings.

THE CONTROLLER

The switch controller is the main operating element of this system (Fig. 1). Its output controls the pulse width-modulated operation of the converter switches to meet power requirements. The specifics of PWM switch operation are common knowledge and will not be described here. The following is a brief description of the requirements that govern the switching action.

Mode Command

The system can be operated under any one of the three modes of Charge, Discharge, and Idle. Presently, the user sets these as a function of time. However, they can be set on the basis of some other operating criteria. There is also a reset mode to start the simulation.

Switch Current Limit

The absolute value of the instantaneous current through each switch is monitored to detect over-current conditions. If one exists, the information is fed to the controller, which then turns off the PWM signal for that switch. In the simulation, it remains so until the start of the next time step.

Motor Current Command

A three-phase, sinusoidal current is generated as a reference for limiting and regulating the phase winding current. The phase winding current is limited for protection and regulated to be sinusoidal to eliminate a substantial amount of the harmonic content. The reference current generator is fed a magnitude and frequency value. At present, the user sets the magnitude, although it could be generated as a function of a system operating condition. The frequency is computed as a time derivative of a sensed rotor position angle.

60° Control

The bidirectional, dc to three-phase, variable frequency ac converter has six switches to control its operation. At any time, switches may be ON, OFF, or PWM switched. Since the three windings are connected together in a star point, current in one winding returns through the other two windings. Hence, it is necessary that the switches connecting the windings to the dc bus be properly operated. Figure 2 shows the back electro-magnetic field (EMF) waveforms for the three phases. The switch connecting phase A to the positive dc bus is denoted by A1, and that connecting to the negative dc bus is denoted by A2. Similarly, switches connected to phases B and C are denoted by B1 and B2, and C1 and C2, respectively. The 180° span is subdivided into three 60° spans as shown. In the 0 to 60° span, the phase A voltage is rising towards its positive peak, the phase B voltage is around its negative peak, and the phase C voltage is falling away from its positive peak. This would suggest that phases A and C should be connected to the positive dc bus and phase B should be connected to the negative dc bus. Also, to maintain the sine wave shape for winding currents, the phase B switch remains ON, while switches for phases A and C are PWM controlled. All other

switches are OFF. The switch operations are similarly coordinated during subsequent 60° intervals. Figure 3 shows operation of the same switches. The PWM mode is shown as a series of pulses. A single wide pulse denotes the ON mode. There are no pulses during the OFF mode.

Appropriate logic signals from the above-described operating requirements become input to the controller, which, in turn, produces commands to operate the converter switches.

MOTOR MODEL

The motor model is the permanent magnet synchronous motor (PMSM) from Saber [5], the same simulation tool used in the previous work. Model data are given below. Motor data are based on a design by Ashman Technologies for a test machine at NASA Glenn.

Motor model (Saber's PMSM library)

Self-inductance of winding, μH	16.7
Back EMF constant per pole pair, $\text{V}/(\text{rad}/\text{sec})$	0.00828
Torque constant per pole pair, Nm/A	0.00828
Motor inertia constant, kg/m^2	0.0001
Winding resistance per phase, $\text{m}\Omega$	14.5
Number of poles	2
First back EMF Fourier coefficient	1

Note: The choice of motor inertia constant value was based on reasonable simulation run time.

SIMULATION PROCEDURE

The basic simulation consisted of charging the flywheel to a reasonably high speed, coasting at that speed, and then discharging the flywheel to a lower speed.

Operating modes

Charge period, sec	0 to 0.4
Idle period, sec	0.401 to 0.475
Discharge period, sec	0.480 to 1

Motor current limits for this simulation

Charge mode, A	100
Discharge mode, A	100, 75, and 50
dc (bus) power supply, V	160
Converter switch current limit, A	150
PWM switching frequency, Hz	8000

Note: The choice of PWM switching frequency is based on reasonable simulation run time.

The simulation run starts at steady state with zero flywheel speed. The inverter circuit outputs voltage and frequency to the motor during the charging process. The motor winding current limit is set at 100 A. Initially, this constitutes charging at constant motor current. Later, as the motor back EMF builds up, the motor current drops down from the limit value. At a selected point in time, the system is signaled into the

Idle mode. This turns all of the switches to OFF, and power transfer becomes zero. The motor maintains whatever speed it has achieved. This is possible only when the machine back EMF cannot discharge through the switch body diode into the dc bus. At a later time, the circuit is pulled off the Idle mode while it is already in the Discharge mode, the two modes being independently controlled. Now the machine, acting as a generator, begins discharging energy from the flywheel into the dc bus at a constant current that is determined by the winding current limit set by the user. Changing the current limit value can change the discharge power. Some other criteria such as "constant power" could be used for charging or discharging.

SIMULATION RESULTS

Figure 4 shows the results from the above described scenario. Figure 4(a) shows the Charge, Discharge, and Idle commands. Figure 4(b) denotes the winding current limits set by the user; there are three separate limits during discharge. Figure 4(c) denotes Machine Speed as it increases, coasts, and then decreases. Figure 4(d) denotes machine back EMF as it mirrors the change in the machine speed. Figure 4(e) shows the machine winding current, which is at the limit value in the beginning and then decreases. When the system goes into Idle mode, the machine current becomes zero. During the Discharge mode, the current follows the three limit values as set by the user.

Figure 5 is a magnified view of the first part of Fig. 4(d) and clearly shows the increasing frequency of the back EMF waveform.

Figure 6 shows a comparison of the winding currents with the corresponding reference currents. The winding current is not smooth because of the PWM switching action. For the selected value of PWM frequency, the discharge current, at 487 Hz, is noisier than the charge current at 135 Hz because more samples per cycle were taken in the latter.

CONCLUSIONS

An improved version of the flywheel energy storage model has been presented. This model incorporates an electro-mechanical machine model, which is able to simulate energy transfer to and from the flywheel. This operation is shown to be explicitly user controlled but can be performed on the basis of some other system operating criteria. This simulation also incorporates improvements made in the controller design for closer regulation of the machine winding current to a sinusoidal form.

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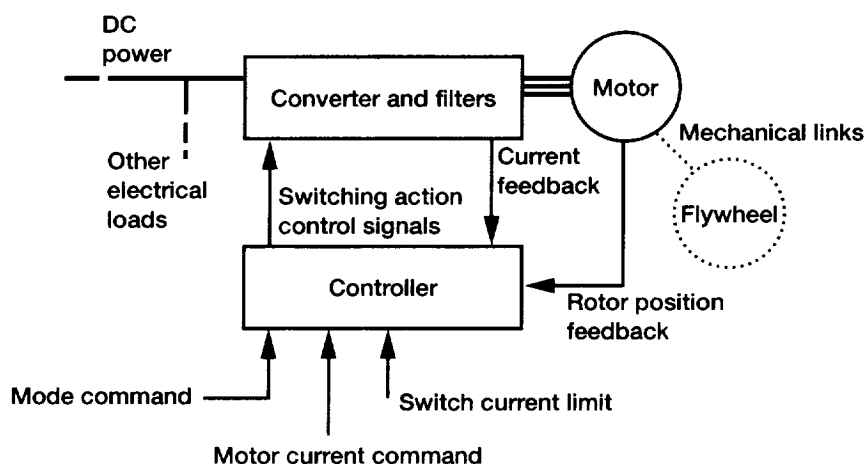


Figure 1.—Simulated flywheel energy storage system.

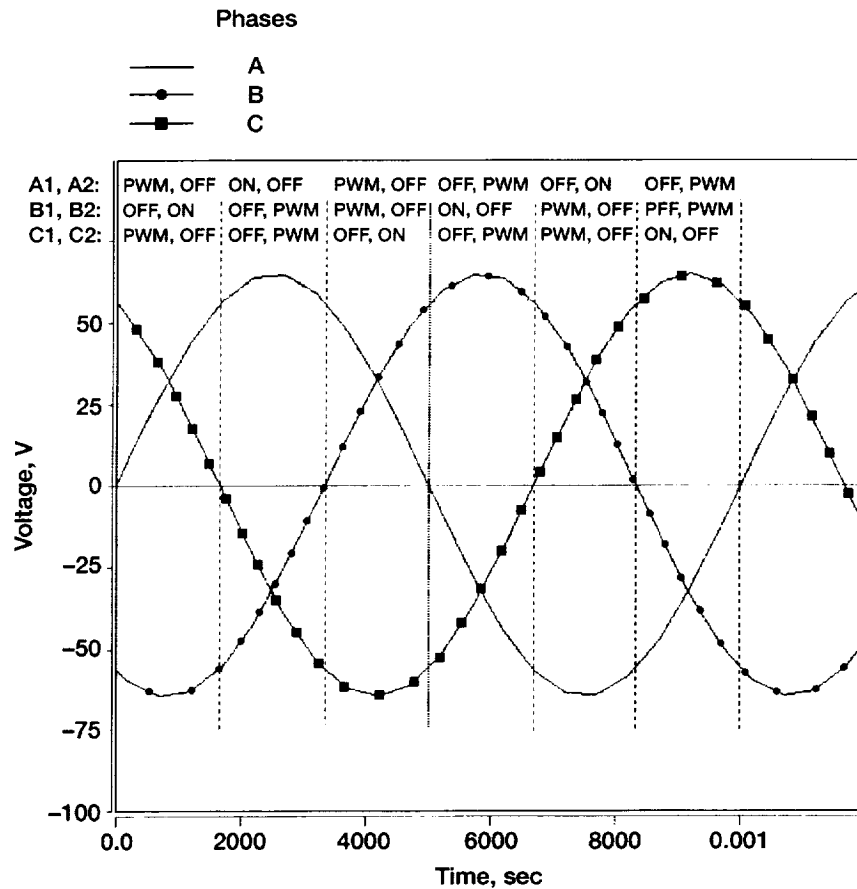


Figure 2.—Motor winding induced voltages (back electromagnetic field (EMF)) with 60° segments highlighted.

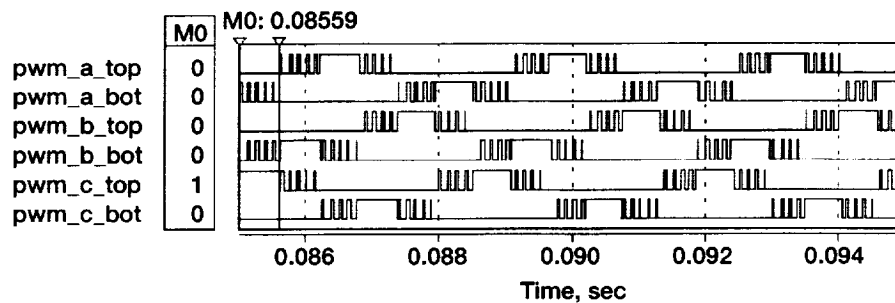


Figure 3.—Details of the 60° PWM controlled signals (pwm_a_top and pwm_a_bot represent phase A; pwm_b_top and pwm_b_bot represent phase B; and pwm_c_top and pwm_c_bot represent phase C). The PWM mode is shown as series of pulses. Single wide pulse denotes ON mode.

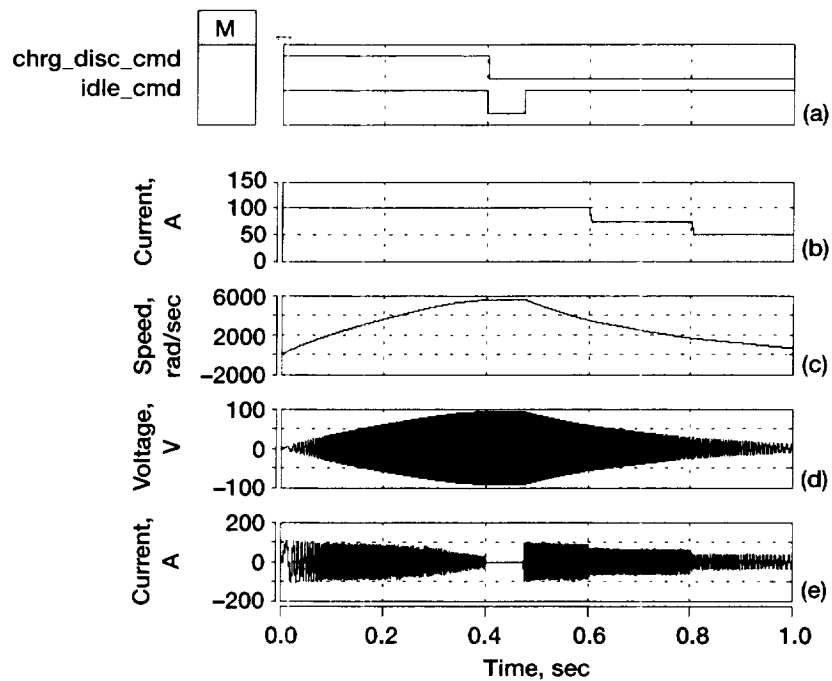


Figure 4.—Some key simulated waveforms. (a) Charge, Discharge, and Idle commands. (b) Winding current limit. (c) Machine speed as it increases, coasts, and then decreases. (d) Machine back EMF. (e) Machine winding current.

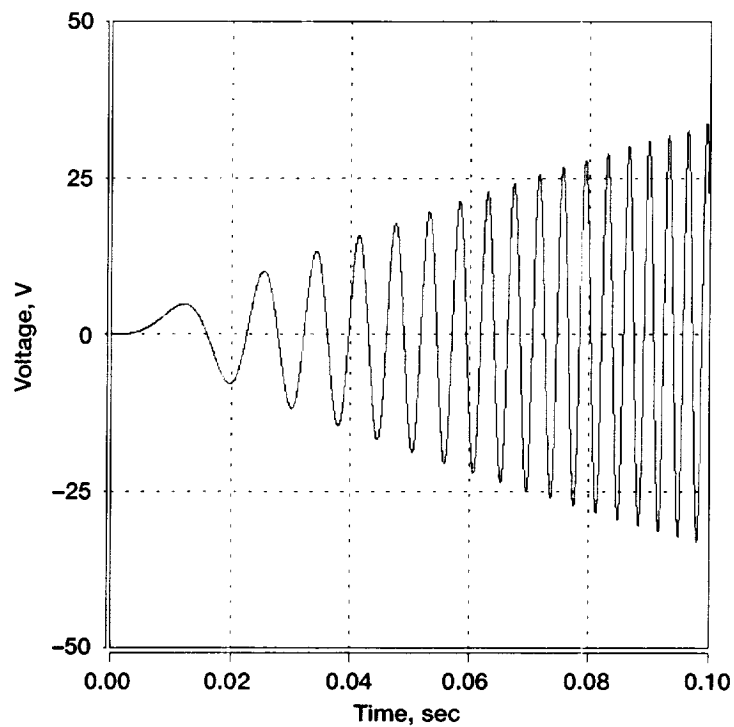


Figure 5.—Expansion of first part of figure 4(d). Increase of both magnitude and frequency of back EMF waveform is clearly shown.

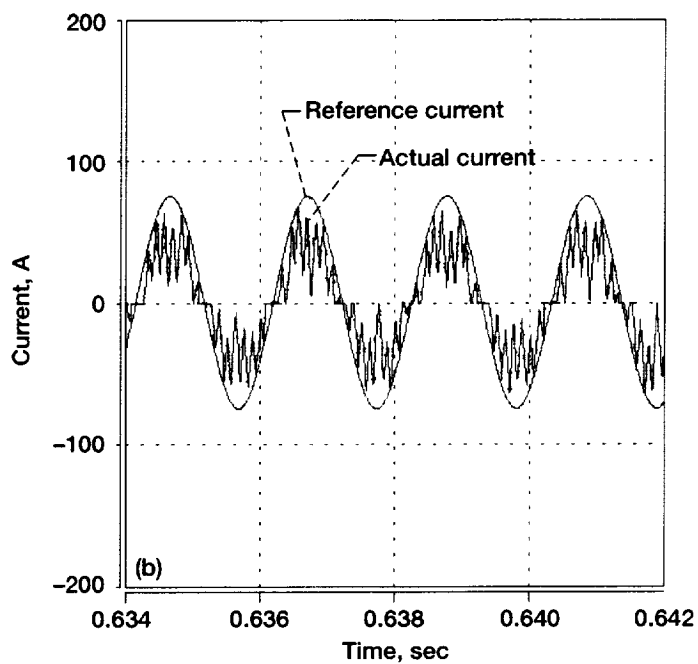
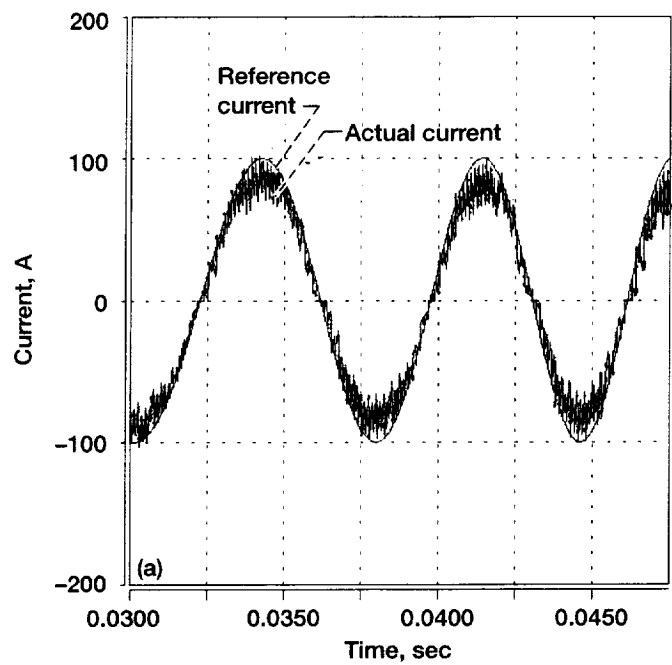


Figure 6.—Comparison of actual winding currents with their corresponding reference currents. (a) During charging from 0.03 to 0.05 sec. (b) During discharging from 0.634 to 0.642 sec.

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